Sliding Mode & Single Input Fuzzy Logic Controllers for Voltage Regulation Of an Asynchronous Wind Turbine Using STATCOM

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Abstract: This paper demonstrate the fiability and the efficiency of a proposed control law based on a combination of sliding mode and single input fuzzy logic controllers, used to command a static synchronous compensator in order to improve voltage profile and stability of an asynchronous wind turbine despite wind speed and load variation. All simulation results as well as the modeling of the wind power system and the design of the proper controllers are described in detail in this document.

Keywords: Asynchronous Wind Turbine; STATCOM; Voltage Regulation; Single Input Fuzzy Logic Controller; Sliding Mode Controllers.

1. INTRODUCTION

In the last decades, the use of renewable energy sources has increased considerably in rural areas, mainly those in hilly and remote regions. Often, an isolated asynchronous wind turbine is the best solution to choose to eliminate the high-cost investment required for transmission line by conventional system.

However, it is well known that reactive power management is the greatest challenge in asynchronous wind turbine based on three-phase Self-Excited Induction Generator (SEIG) [1] [2]. Any variation of wind speed or load causes a variation on the needed reactive power and thus a voltage fluctuation. Flexible AC transmission (FACT) device such as STATCOM become then a necessity to prevent voltage instability and hence voltage collapse at the point of common coupling (PCC) [3] [4] [5].

Basically, there are two control objectives implemented in STATCOM. One is the PCC voltage regulation and the other is DC voltage regulation across its capacitor [6]. In conventional scheme, a decoupled dq axis control approach based on four proportional integral (PI) type cascaded controllers is usually used [7]. The problem of this methods is that the control design depends on the operating point. This is not well advised in the event of large disturbances. Furthermore, the chosen set of the PI gains are held fixe during operation of STATCOM. Since wind speed and load changes with time those parameters cannot be suitable for all working conditions.

Hence, other control strategies based on adaptive PI control have been proposed to track the variations [9][10]. However, these controllers need mathematical models of the studied system and are therefore sensitive to parameter variation.

Therefore, to reduce voltage fluctuation at all possible conditions we propose a new structure based on a combination of sliding mode and single input fuzzy logic controllers. The proposed controllers have a simple structure, needs a low computations time, have a good self-tuning ability and depends only on the error between the reference and the measured value to reduce voltage fluctuation at all possible conditions. Therefore, this control approach can be easily used in real time implementation.

The organization of this paper is as follows. It starts with the modelling of the studied asynchronous wind turbine and STATCOM, then focuses on the description of the proposed control scheme and the design of the proper regulators, to finally discuss and analysis the simulated results.
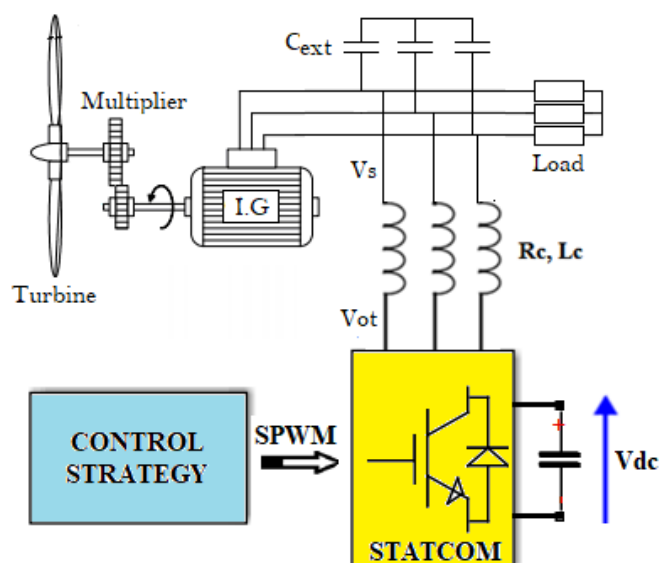

Fig. 1. Wind energy conversion system diagram

2. SYSTEM DESCRIPTION & MODELLING

The block diagram of the studied system is shown in Fig. 1. It consists of a three-bladed wind turbine driving a self-excited induction generator through a speed gain multiplier M and a static synchronous compensator for voltage regulation.

2.1. Wind Turbine Modelling

The aerodynamic power P_{aer} extracted from the wind turbine along with the aerodynamic torque are expressed through the following relations respectively [1]:

$$P_{aer} = C_p(\lambda).\frac{\rho.\pi.R^2.V^3}{2} \tag{1}$$

$$C_{aer} = \frac{P_{aer}}{\Omega_{turb}} = C_p(\lambda)\frac{\rho.\pi.R^2.V^3}{2.\Omega_{turb}} \tag{2}$$

2.2. Multiplier

The torque and the mechanical speed transmitted from the wind turbine to the shaft of the induction generator are:

$$C_g = \frac{C_{aer}}{M} \tag{3}$$

$$\Omega_{mec} = \frac{\Omega_{turb}}{M} \tag{4}$$

2.3. Self-Excited Induction Generator Modelling

The mathematical model of the asynchronous generator in dq reference frame is described as follows:

$$
\begin{aligned}
V_{sd} &= R_s.i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_s.\varphi_{sq} \\
V_{sq} &= R_s.i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_s.\varphi_{sd} \\
V_{rd} &= 0 = R_r.i_{rd} + \frac{d\varphi_{rd}}{dt} + (\omega_s - \omega_r).\varphi_{rq} \\
V_{rq} &= 0 = R_r.i_{rq} + \frac{d\varphi_{rq}}{dt} - (\omega_s - \omega_r).\varphi_{rd}
\end{aligned}
\tag{5}
$$

$$
\begin{aligned}
\varphi_{sd} &= L_s.i_{sd} + L_m.i_{rd} \\
\varphi_{sq} &= L_s.i_{sq} + L_m.i_{rq} \\
\varphi_{rd} &= L_m.i_{sd} + L_r.i_{rd} \\
\varphi_{rq} &= L_m.i_{sq} + L_r.i_{rq}
\end{aligned}
\tag{6}
$$

The dynamic equation of the mechanical motion can be given as:

$$J_t\frac{d\Omega_{mec}}{dt} = C_g - C_{em} - f_{vis}.\Omega_{mec} \tag{7}$$

Where:

$$C_{em} = p.\frac{L_m}{L_r}(\varphi_{rd}.i_{sq} - \varphi_{rq}i_{sd}) \tag{8}$$

$$J_t = \frac{J_{turb}}{M^2} + J_g \tag{9}$$

The self-priming of the IG is done via a capacitive bench, if connected to a resistive load R they are represented by:

$$\frac{dV_{sd}}{dt} = \frac{-1}{C_{ext}}.i_{sd} - \frac{1}{RC_{ext}}.V_{sd} \tag{10}$$

$$\frac{dV_{sq}}{dt} = \frac{-1}{C_{ext}}.i_{sq} - \frac{1}{RC_{ext}}.V_{sq} \tag{11}$$

2.4. STATCOM Modelling

The equations describing the AC side of STATCOM in the synchronous reference frame are given by:

$$\frac{d}{dt}\begin{bmatrix}i_{otd}\\i_{otq}\end{bmatrix} = \begin{bmatrix}-\frac{R_c}{L_c} & \omega_s \\ -\omega_s & -\frac{R_c}{L_c}\end{bmatrix}.\begin{bmatrix}i_{otd}\\i_{otq}\end{bmatrix} + \frac{1}{L_c}\begin{bmatrix}V_{sd} - V_{otd}\\V_{sq} - V_{otq}\end{bmatrix} \tag{12}$$

Where ω_s the pulsation of the generated voltage V_s.

The voltage and current are related in the DC side of STATCOM by the following equation:

$$\frac{dV_{dc}}{dt} = \frac{i_{dc}}{C_{dc}} \tag{13}$$

Since SPWM technique is used in STATCOM, and all the voltage harmonics produced by the inverter are neglected, the equations relating the dc-side and ac-side can be written as:

$$\begin{bmatrix}V_{otd}\\V_{otq}\end{bmatrix} = MI.V_{dc}.\begin{bmatrix}\cos(\alpha)\\\sin(\alpha)\end{bmatrix} \tag{14}$$

$$i_{dc} = MI.\begin{bmatrix}i_{otd} & i_{otq}\end{bmatrix}.\begin{bmatrix}\cos(\alpha)\\\sin(\alpha)\end{bmatrix} \tag{15}$$

Where MI the Modulation Index and α the firing angle are the control variables of STATCOM, deduced from the voltage references by:

$$MI = \frac{\sqrt{V_{otd\_ref}^2 + V_{otq\_ref}^2}}{V_{dc}} \tag{16}$$

$$\alpha = \tan^{-1}(\frac{V_{otq\_ref}}{V_{otd\_ref}}) \tag{17}$$

3. CONTROL STRATEGY

In order to improve the performance of the asynchronous wind turbine, STATCOM will exchange reactive power with the SEIG to reduce the AC voltage fluctuation and will absorb active power to keep the DC voltage at its rated value.

In dq coordinate, each of the current components has clear physical meaning. As we can see from (18) the d-axis current component *iotd* contributes to the control of the instantaneous active power *P(t)*, while the q-axis one *iotq* contributes to the control of the instantaneous reactive power *Q(t)* :

$$P(t) = \frac{3}{2}v_{sd}i_{otd} \tag{18}$$

$$Q(t) = -\frac{3}{2}v_{sd}i_{otq} \tag{19}$$

From (12) both components of the current are cross-coupled through the term $\omega_s L_c$. The decoupling of the active and reactive current become then necessary. In this work the classical decoupled watt-var method is used.

The two new variables introduced in (20) and (21) represent the output from the control system.

$$V_{otd}{}^* = i_{otq}\omega_s L_c + V_{sd} - V_{otd\_ref} \tag{20}$$

$$V_{otq}{}^* = i_{otd}\omega_s L_c + V_{sq} - V_{otq\_ref} \tag{21}$$

The adopted control strategy shown in Fig. 2 contains so two loops. In the outer loop, the AC voltage and the DC voltage should be regulated to their reference values via a SIFLC and a sliding mode controller respectively. While in the inner loop, the injected currents *iotd* and *iotq* are adjusted to follow their reference values *iotq** and *iotd** using sliding mode controllers as well.
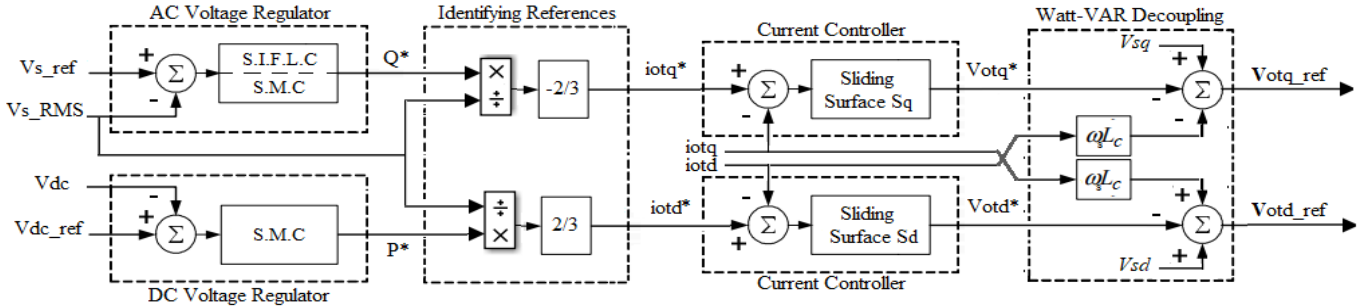

Fig. 2. Proposed voltage control structure

3.1. Current controllers design

- Sliding Surface:

The control objectives are to track or slide along the predefined current components references *iotdq**. For this purpose, the sliding surfaces are set as:

$$S_d = i_{otd} - i_{otd}^* \tag{22}$$

$$S_q = i_{otq} - i_{otq}^* \tag{23}$$

The sliding surfaces derivatives are given respectively as:

$$\frac{dS_d}{dt} = -k_d sign(S_d) \tag{24}$$

$$\frac{dS_q}{dt} = -k_q sign(S_q) \tag{25}$$

Where k_d and k_q are positive constants.

However, from (22) and (23) we have:

$$\frac{dS_d}{dt} = \frac{di_{otd}}{dt} - \frac{di_{otd}^*}{dt} \tag{26}$$

$$\frac{dS_q}{dt} = \frac{di_{otq}}{dt} - \frac{di_{otq}^*}{dt} \tag{27}$$

From (12), (20) and (21), we can write:

$$\frac{di_{otd}}{dt} = -\frac{R_c}{L_c}i_{otd} + \frac{V_{otd}{}^*}{L_c} \tag{28}$$

$$\frac{di_{otq}}{dt} = -\frac{R_c}{L_c}i_{otq} + \frac{V_{otq}{}^*}{L_c} \tag{29}$$

Thus, STATCOM voltage references are calculated as follow:

$$V_{otd\_n}{}^* = -L_c k_d sign(S_d) + R_c i_{otd} \tag{30}$$

$$V_{otq\_n}{}^* = -L_c k_q sign(S_q) + R_c i_{otq} \tag{31}$$

When the sliding mode occurs on the sliding surface, then $S_{dq} = \dot{S}_{dq} = 0$, and therefore the dynamic behaviour of the tracking problem is equivalently governed by the following equations:

$$\frac{dS_d}{dt} = \frac{di_{otd}}{dt} - \frac{di_{otd}^*}{dt} = -\frac{R_c}{L_c}i_{otd} + \frac{V_{otd_{eq}}{}^*}{L_c} = 0 \tag{32}$$

$$\frac{dS_q}{dt} = \frac{di_{otq}}{dt} - \frac{di_{otq}^*}{dt} = -\frac{R_c}{L_c}i_{otq} + \frac{V_{otq_{eq}}{}^*}{L_c} = 0 \tag{33}$$

So, we can write:

$$V_{otd\_eq}{}^* = R_c i_{otd} \tag{34}$$

$$V_{otq\_eq}{}^* = R_c i_{otq} \tag{35}$$

Finally, the sliding mode current controllers are designed as:

$$V_{otd}{}^* = V_{otd_n}{}^* + V_{otd_{eq}}{}^*$$
$$V_{otd}{}^* = -L_c k_d sign(S_d) + R_c i_{otd} + R_c i_{otd} \tag{36}$$

$$V_{otq}{}^* = V_{otq_n}{}^* + V_{otq_{eq}}{}^*$$
$$V_{otq}{}^* = -L_c k_q sign(S_q) + R_c i_{otq} + R_c i_{otq} \tag{37}$$

- Stability analysis:

A Lyapunov function is necessary so that the existence of the sliding mode is determined. It is defined by the following expression:

$$V = \frac{1}{2}S_d^2 + \frac{1}{2}S_q^2 \tag{38}$$

To guarantee the attraction of the system throughout the surface, the following condition must be respected:

$$\dot{V} < 0 \tag{39}$$

By differentiating (38), we have:

$$\dot{V} = S_d \dot{S}_d + S_q \dot{S}_q \tag{40}$$

Replacing (24) and (25) into (40), we obtain:

$$\dot{V} = -S_d k_d sign(S_d) - S_q k_q sign(S_q) \tag{41}$$

It results:

$$\dot{V} = -k_d |S_d| - k_q |S_q| < 0 \tag{42}$$

Consequently, we have proved that the global asymptotical stability is ensured.

3.2. AC voltage controller design

The proposed controller is constructed by choosing the error between the referenced and the measured RMS value of the asynchronous wind turbine generated voltage as an input signal and dQ^* as output signal, Fig.3.
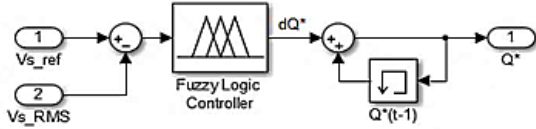

Fig. 3. AC voltage regulator

The reference reactive power to exchange with the induction generator in order to maintain the AC voltage stable is calculated using the following expression:

$$Q^* = \sum dQ^*(t) \tag{43}$$

- If error is equal to zero then Vs_RMS is equal to Vs_ref value, dQ^* must be equal to zero to keep Q^* at its previous value to avoid injection or absorption of any reactive power.

- If error is negative then Vs_RMS is greater than Vs_ref value (inductive mode), dQ^* must be positive as well as Q^* and its value should increase to absorb the excess of reactive power forcing so the generated voltage to drop to the rated value.

- If error is positive then Vs_RMS is less than Vs_ref value (capacitive mode), dQ^* must be negative as well as Q^* and its value should decrease to inject the needed reactive power forcing so the generated voltage to rise up to the rated value.

We define a simple structure for the fuzzy controller Mamdani-type with seven triangular rule-based-membership functions. Fig. 4 shows input and output membership functions of the proposed SIFLC.
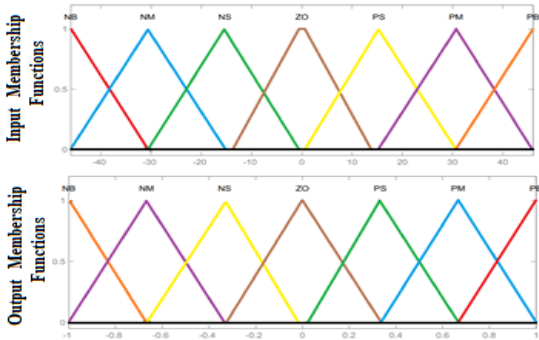

Fig. 4. Input and output membership functions of the SIFLC

The seven linguistic variables used are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZO), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The 7 rules have been built as represented in Fig. 5.
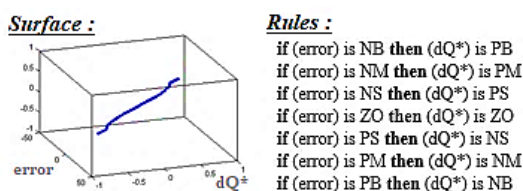

Fig. 5. The chosen rules of the SIFLC

It has been noticed that the single input fuzzy logic controllers act like a sliding mode controller but with a variable step. Equation (44) is then introduced to compare the performance of the two controllers.

$$dQ^* = -k_{ac} \, \text{sign}(V_{s\_ref} - V_{s\_RMS}) \tag{44}$$

3.3. DC voltage controller design

The active power STATCOM need to absorb from the wind turbine system to compensate losses in the DC circuit is deduced from the following sliding surface:

$$S_p = V_{dc} - V_{dc\_ref} \tag{45}$$

The sliding surface derivative is given by:

$$\frac{dS_p}{dt} = -k_p \, sign(S_p) \tag{46}$$

Where k_p is a positive constant. From (45) we have:

$$\frac{dS_p}{dt} = \frac{dV_{dc}}{dt} - \frac{dV_{dc\_ref}}{dt} \tag{47}$$

However, we know that:

$$\frac{dV_{dc}}{dt} = \frac{i_{dc}}{C_{dc}} = \frac{P_{dc\_n}}{C_{dc}.V_{dc}} \tag{48}$$

From (46), (47) and (48) we can write:

$$P_{dc\_n} = -k_p.C_{dc}.V_{dc}.sign(S_p) \tag{49}$$

The expression of the equivalent control laws in this case is null, and can be deduced from (48) by assuming that $\dot{S}_p = 0$:

$$\frac{dS_p}{dt} = \frac{dV_{dc}}{dt} - \frac{dV_{dcref}}{dt} = \frac{i_{dc}}{C_{dc}} = \frac{P_{dceq}}{C_{dc}.V_{dc}} = 0 \tag{50}$$

So, we can write:

$$P_{dc}{}^* = P_{dc\_n}{}^* = -k_p.C_{dc}.V_{dc}.sign(S_p) \tag{51}$$

The stability of the chosen surface for DC voltage control can be verified by following the same method used in sliding surface current controllers.

4. SIMULATION RESULTS & DISCCUSSION

Fig. 6 shows the profile of the generated RMS voltage when the asynchronous wind turbine is under varying wind speed and load conditions for both no compensation mode and compensation mode.

During the starting phase from the instant 0s to 2s, STATCOM is not yet connected because the produced voltage has not reached the regulation zone set to +/-20% of Vs_ref. After the second two, when the single input fuzzy logic controller is connected, Vs_RMS reaches 254.4V then drops in 0.5s to 230V which can be considered as a good transient response since the overshoot is around 10%. At the 4th second and 6th second when wind speed drops from 10.5m/s to 8m/s then rises again to 9m/s at no load, Vs_RMS changes also but using the proposed approach STATCOM was capable of regulating the generated voltage in 0.4s and 0.46s respectively.

Finally, when the system become at full load at the 8th second the proposed control strategy has once more proved its efficiency because Vs_RMS drops to 183V then stabilizes at the rated value in less than 0.03s.

Otherwise, the SMC introduced in equation (44) has also shown good tracking performance and better dynamic responses but the chattering phenomenon observed in the steady state is its big inconvenient.

However, we can conclude that the proposed controllers (SMC or SIFLC) can effectively maintain the self-excited induction generator voltage terminals at its referenced value with very satisfying dynamic and static responses.
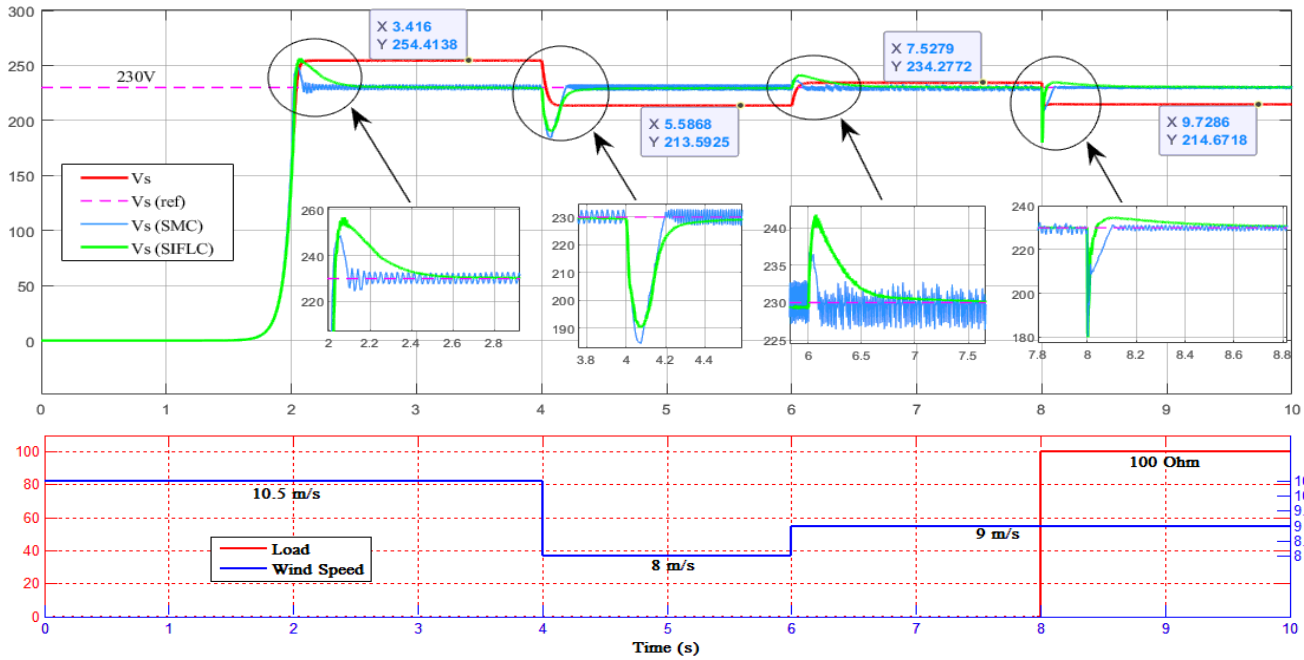

Fig. 6. Asynchronous wind turbine voltage with and without compensation at different wind speed and load state

To be able to reduce AC voltage fluctuations, the SIFLC as well as SMC had to respond to wind speed and load variation with good dynamic forcing so STATCOM to operate in both capacitive and inductive mode. Fig. 7 shows the exchanged reactive power between the SEIG and STATCOM at different states.
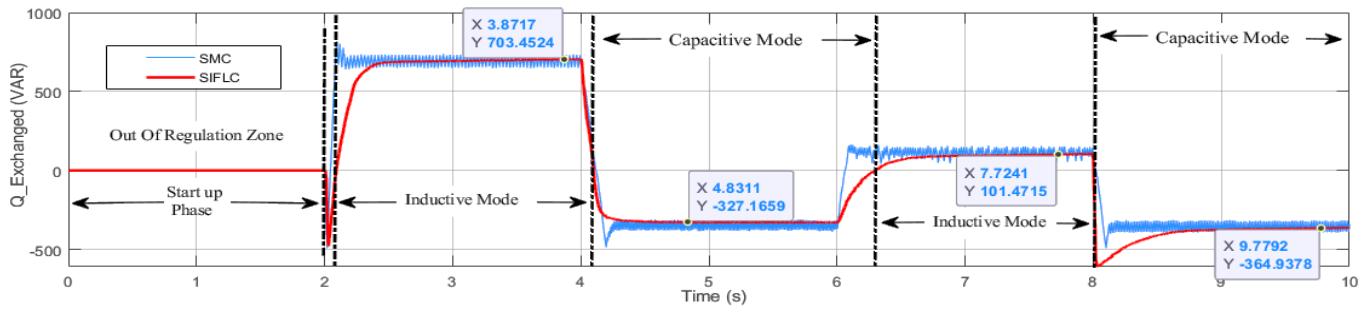

Fig. 7. The exchanged reactive power between STATCOM and the asynchronous wind turbine.

Furthermore, in Fig. 8 the injected current $iotq$ contributing to control the exchanged reactive power presents in the case of SIFLC a good tracking responses and robust characteristics.

The observed chattering in the steady state is acceptable due to its small variation and can be reduced in practice by selecting an optimal value of k_q.
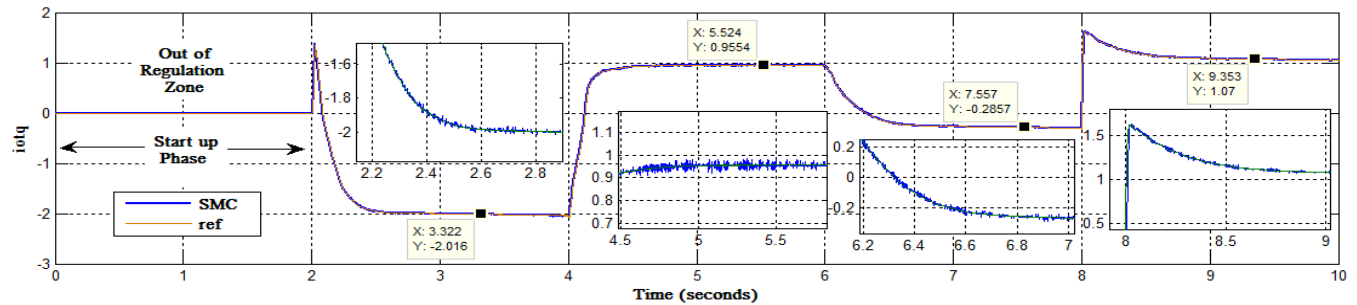

Fig. 8. STATCOM q_axes current variation as function of PCC voltage using SMC

In the other part, simulation results observed in Fig.9 shows that the designed sliding mode DC voltage controller was able, at t=2s, to rise *Vdc* up to the referenced value just after the excitation of the SEIG.
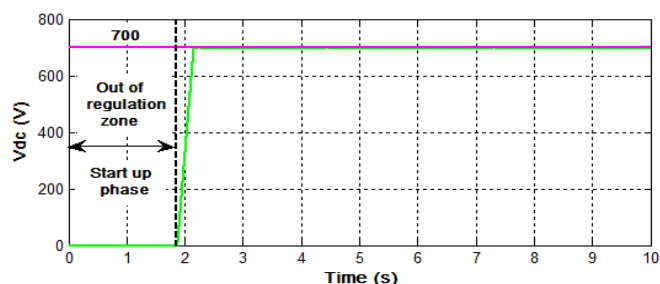

Fig. 9. Sliding Mode DC voltage response

The active power provided by the asynchronous wind turbine to STATCOM to regulated *Vdc* reaches in Fig.10 the value of 28.5W then falls to zero after 0.7 seconds since all losses are neglected.
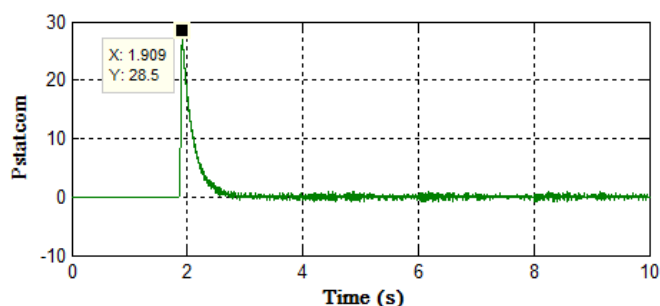

Fig.10. STATCOM absorbed active power

The current controller presented in Fig. 11 has a good convergence characteristics which contribute to a good control performance of the active power exchanged between SEIG and STATCOM.
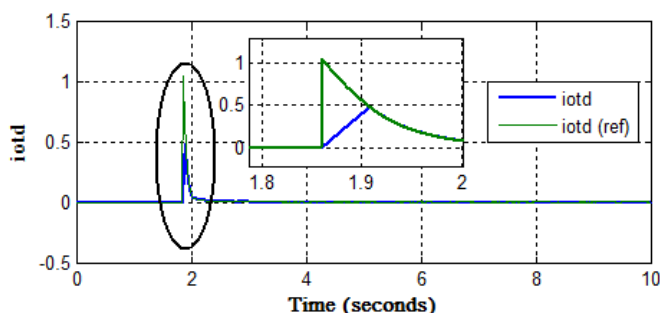

Fig. 11. STATCOM d_axes current variation

5. CONCLUSION

This paper presented a novel voltage control strategy for asynchronous wind turbine based on STATCOM. The proposed configuration employs single input fuzzy logic and sliding mode approach in order to calculate the required converter's control references to eliminate the instantaneous errors of AC and DC voltage. The effectiveness of the current control loops has been first confirmed by the theoretical investigation that proved its convergence. Then the validity of the proposed voltage control scheme has been established through simulation results analysis that have shown excellent characteristics of voltage profile regarding response time, references tracking, disturbance rejection and robustness.

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